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April 29, 2003

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APPLICATION NUMBER: ***60/373,236***
FILING DATE: ***April 17, 2002***
RELATED PCT APPLICATION NUMBER: ***PCT/US03/10219***

By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS

M. Tarver

M. TARVER
Certifying Officer

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4-18-02

A/Prov

Our Docket No.: S697.12-0064

JC857 U.S. PTO 04/17/02

JC872 U.S. PTO 60/373236 04/17/02

PROVISIONAL PATENT APPLICATION

ENTITLED:

LAYERED DEPOSITION BRIDGE TOOLING

INVENTOR(S):

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ENCLOSURES

X Specification (with attached Appendix A); Number of Pages 37

X Drawings; Number of Sheets 3

X A check in the amount of $80.00.

X Applicant claims small entity status. See 37 C.F.R.1.27

X Fee Transmittal

X File Data Sheet

Respectfully submitted,

KINNEY & LANGE, P.A.

By: [signature]
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Express Mail No. EL763828835US

Date of Deposit: April 17, 2002

FEE TRANSMITT

Complete if Known	
Application No.	
Filing Date	Herewith
First Named Inventor	William R. Priedeman, Jr.
Group Art Unit	
Examiner Name	
Atty. Docket Number	S697.12-0064

Total Amount of Payment $80.00

METHOD OF PAYMENT (Check One)

1. [X] The Commissioner is hereby authorized to charge any additional fee required under 37 C.F.R. 1.16 and 1.17 and credit any over payments to Deposit Account No.11-0982. Deposit Account Name Kinney & Lange, P A

2. [X] Check Enclosed

FEE CALCULATION

1. BASIC FILING FEE

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description
101	740	201	370	[ ] Utility Filing Fee
106	330	206	165	[ ] Design Filing Fee
108	740	208	370	[ ] Reissue Filing Fee
114	160	214	80	[X] Prov Filing Fee

Subtotal (1) $80.00

2. EXTRA CLAIM FEES

	Number Claims		Prior		Extra		Fee from Below		Fee Paid
Total	_	-	_	=	_	X	_	=	_
Indep.	_	-	_	=	_	X	_	=	_
Multiple Dependent Claims							_	=	_

Insert 3 and 20, or number previously paid if greater, Reissue see below

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Description
103	18	203	9	Claims in excess of 20
102	84	202	42	Independent claims in excess of 3
104	280	204	140	Multiple Dependent Claim
109	84	209	42	Reissue Independent Claims Over Original Patent
110	18	210	9	Reissue claims in excess of 20 and over original patent

Subtotal (2) $-0-

FEE CALCULATION (Continued)

3. ADDITIONAL FEES

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee paid
105	130	205	65	Surcharge - Late filing fee or oath	_
127	50	227	25	Surcharge - late provisional filing fee or cover sheet	_
139	130	139	130	Non-English specification	_
147	2,520	147	2,520	For Filing a Request for Reexamination	_
115	110	215	55	Extension for reply within first month	_
116	400	216	200	Extension for reply within second month	_
117	920	217	460	Extension for reply within third month	_
118	1,440	218	720	Extension for reply within fourth month	_
128	1,960	280	980	Extension for reply within fifth month	_
120	320	220	160	Filing a brief in support of an appeal	_
121	280	221	140	Request for oral hearing	_
148	110	248	55	Terminal Disclaimer Fee	_
140	110	240	55	Petition to revive - unavoidable	_
141	1,280	241	640	Petition to revive - unintentional	_
142	1,310	242	670	Utility/Reissue issue fee (inc. advance copies)	_
143	490	243	260	Design issue fee (inc advance copies)	_
122	130	122	130	Petitions to the Commissioner	_
123	50	123	50	Petitions related to provisional applications	_
126	180	126	180	Submission of Information Disclosure Statement	_
581	40	581	40	Recording each patent assignment per property (times number of properties)	_
179	740	279	370	Request for Continued Examination (RCE)	_

Other fee (specify) ______________________ _

Subtotal (3) $-0-

Signature [signature] Gena M. Chapman

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Date 4/17/02

Deposit Account No. 11-0982

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Application Information

Title Line One:: Layered Deposition Bridge Tooling
Title Line Two::
Total Drawing Sheets:: 3
Formal Drawings?:: No
Application Type:: Provisional
Docket Number:: S697.12-0064
Licensed US Govt. Agency::
Contract or Grant Numbers::
Secrecy Order in Parent Application?::

Representative Information

Representative Customer Number:: 00164

Continuity Information

This application is a::
> Application One::
Filing Date::
Patent Number::
which is a::
>> Application Two::
Filing Date::
Patent Number::

Prior Foreign Applications

Foreign Application One::
Filing Date::
Country::
Priority Claimed::

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LAYERED DEPOSITION BRIDGE TOOLING

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application is a continuation-in-part of application serial no. 10/019,160, filed October 19, 2001, which is a 371 of PCT/US00/10592 filed April 19, 2000, which is a non-provisional of provisional application serial no. 60/130,165 filed April 20, 1999.

BACKGROUND OF THE INVENTION

The present invention relates to prototyping of injection molded objects, and more particularly to methods for rapidly making mold tools for use in plastic injection molding prototyping processes.

In a typical injection molding process, plastic is injected at high pressures, extremely quickly, into a thermally conductive metal mold. The molded part is quickly cooled to a temperature at which it can be removed from the mold. The part is then quickly ejected from the mold so that another part can be made, and so that the part does not become stuck on the mold (due to shrink differential). Cooling of large parts continues on a fixture. The goals of production injection modeling are to produce a high quantity of high-quality parts in a short turn-around time. A thirty second cycle time or less for the making of each molded part is typical.

In order to produce a three-dimensional object in a typical injection molding process, it is necessary to prepare a mold tool that has a cavity which is complementary to the desired shape of the three-dimensional object. The mold tool generally consists of two opposing halves, which mate together to define the mold cavity. The mold tool is normally machined out of steel or other metal which is capable of withstanding high temperature and pressure when hot liquid is injected into the mold. In use, the mold tool is inserted into a frame of an injection molding machine, and held in place with high clamping forces to oppose pressure generated inside the mold. The time and skill required to prepare the mold tool are both significant. The machining must be done by skilled craftsmen, and includes the incorporation of a sprue through which the molding material is injected, a vent,

cooling lines and ejector pins. Typically, this process involves placing an order with an outside vendor and waiting several weeks or months for delivery, at high cost.

Before undergoing the expense and long lead time associated with conventional metal mold manufacturing, it is desirable to produce a prototype of the part that will have similar characteristics to the production part. The goal is produce a prototype having characteristics sufficiently close to that of the desired final manufactured part so as to permit a close prediction of part performance. Various additive process rapid prototyping (RP) technologies are commonly used to make prototype parts in the design stages of a part. These rapid prototyping technologies include fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), laminated object manufacturing (LOM) and jet technology. These additive process techniques produce prototypes useful for evaluating the fit, form and function of a part design, to gain preliminary part approval and to accelerate product development. The strength of a final production part is not, however, replicated in prototypes created by these rapid prototyping techniques. The additive processes create layers, layered stress points and voids in the part resulting in a different internal stress structure than that of the homogeneous injection-molded part. Additionally, many materials used in these processes are weak.

Various methods have been developed for creating mold tools used to make prototype injection molded parts, which may be referred to as "bridge tooling" or "temporary tooling." A number of these methods utilize rapid prototyping techniques, particularly, stereolithography. For example, U.S. Patent No. 5,439,622 describes the use of stereolithography to form a mold shell, which is then reinforced with an incompressible material and coated with a thermally conductive material. U.S. Patent No. 5,989,679 describes a mold tool formed by injecting a strengthening material into cavities within an object formed by stereolithography.

U.S. Patent No. 5,952,018 describes a mold tool, including an ejection valve within the mold tool, formed by stereolithography. U.S. Patent No. 5,641,448 describes the making of a mold tool by depositing a metal coating onto a plastic mold shell produced by stereolithography.

The use of rapid prototyping to create molds for use in processes other than injection molding are also known. For example, U.S. Patent No. 6,073,056 describes a mold built by stereolithography or fused deposition modeling used to form a vacuum cast part. U.S. Patent No. 6,103,156 describes the making of a prototype part by pouring a thermoset into a mold formed by a rapid prototyping technique.

Techniques are also known which use a part formed a rapid prototyping process as a master mold pattern to create a prototype mold tool. For example, U.S. Patent No. 5,189,781 describes the use of a prototype part as the pattern for making a sprayed metal mold. U.S. Patent No. 5,707,578 uses a prototype created by stereolithography as a master mold.

A commercial process known as the Swiftool™ process uses a prototype part, which may be made by a rapid prototyping technique, as a pattern for creating bridge tooling. The process takes several days. Another commercial process known as 3D Keltool® makes bridge tooling in a period of several days in a metal-powder sintering process, starting from a master pattern made by stereolithography. Yet another commercial system called AIM™ builds mold tools by stereolithography using UV-sensitive materials.

While the above-described methods do reduce the time and expense of making mold tools, such methods nonetheless require finishing steps which can be tedious and which require additional time and skill to complete. There is a need for a more rapid and low cost method of making a mold tool which can be used to create a small number of prototype injection molded parts.

BRIEF SUMMARY OF THE INVENTION

The present invention is a method for making a prototype plastic injection molded part using a mold tool made by a fused deposition modeling technique. In one embodiment, the mold tool is built in two or more portions, wherein layers of thermally solidifiable material are deposited in a predetermined pattern according to computer file data representing the mold shape. Each mold portion includes a mold surface, a mating surface, and a base which supports the mold and mating surfaces. Together the mold portions define a mold cavity. A sprue channel and alignment holes are either formed into the mold tool as it is built, or machined into the mold tool after it is built. A vent channel may likewise be built or machines into the mold tool, or, the build process itself may be designed to result in the mold tool itself having a porosity sufficient to vent the tool. Optionally, the mold surfaces and mating surfaces may be smoothed by a vapor smoothing process to remove unintentional ridges in the surfaces. The mold tool is used in an injection molding machine, without the addition of any reinforcement fill material or layers, to create the prototype part.

In an alternate embodiment, the mold tool is made from a soluble modeling material and has a single-piece construction.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a top plan view of two mold portions of an exemplary mold tool produced by fused deposition modeling in accordance with the present invention.

Figure 2 is a sectional view of the mold portions of FIG. 1, taken along a line 2-2 of FIG. 1 and mated together to define a mold cavity.

Figure 3 is a flow diagram of the process of making a prototype injection molded part using a mold tool built in accordance with the present invention.

DETAILED DESCRIPTION

Figure 1 shows two halves of an exemplary mold tool 10 built in accordance with the present invention. A first portion 12 of mold tool 10 includes a recessed mold surface 14 corresponding to the shape of a first half of a desired prototype molded part. A second portion 16 of mold tool 10 includes a recessed mold surface 18 corresponding to the shape of a second half of the desired prototype molded part. The mold portions 12 and 16 each have a mating surface 17 and a base 20 shown in FIG. 2, which supports the mold surfaces 14 and 18 and the mating surfaces 17. When the mating surfaces 17 of the mold portions 12 and 16 are mated together as shown in FIG. 2, the mold surfaces 14 and 18 define a mold cavity 19, which has the shape of the desired prototype part. For prototype molded parts that have interior cavities, the mold tool 10 further comprises a mold core.

The mold portions 12 and 16 each also include a sprue channel 22, a vent channel 24, and four alignment holes 26. The sprue channels 22 allow for the placement of a sprue which will be inserted in a final assembly of the mold tool 10, providing a path for the injection of molten plastic into the mold cavity 19. The vent channels 24 together form a passage for the venting of gas from the mold cavity 19 when the mold tool 10 is assembled.

The alignment holes 26 receive screws or pins, which align and hold together the mold tool portions 12 and 16 in assembly of the mold tool 10. The mold tool 10 may also optionally include cooling lines for introducing a flow of coolant during an injection process.

In an alternate embodiment, a mold tool is made from a soluble modeling material and has a single-piece construction. The soluble material permits a single-piece construction, as the molt tool may be dissolved from a prototype part after the part is formed. In contrast, a mold tool made from an insoluble material is removed from a prototype part by mechanically disengaging the mold portions. A suitable soluble modeling material is an alkali-soluble material comprising a base polymer

containing a carboxylic acid, and a plasticizer. The base polymer comprises a first comonomer (which contains carboxylic acid) and a second comonomer that is polymerized with the first comonomer to provide thermal and toughness properties suitable for fused deposition modeling. A preferred base polymer is comprised of methacrylic acid as the first comonomer and an alkyl methacrylate (e.g., methyl, ethyl, propyl or butyl methacrylate, and combinations thereof), preferably methyl methacrylate, as the second comonomer. A desirable amount of the acid-containing first comonomer is 15-60 weight percent of the base polymer. The base polymer is plasticized to attain rheological properties desired for the modeling process. Most preferably, the alkali-soluble thermoplastic material contains between about 84 weight percent and 74 weight percent of the base polymer and contains between about 16 weight percent and 26 weight percent of the plasticizer, and has a melt flow index of between about 5 g/10 minutes and 10 g/10 minutes under a load of 1.2 kg at 230 °C. A mold tool made from the alkali-soluble material is removed from the prototype part by placing the mold tool containing the part in an alkaline bath. The alkali-soluble modeling material is the subject of co-pending U.S. Patent application serial no.10/019,160, which is hereby incorporated by reference as if set forth fully herein.

The mold tool of the present invention is built by a fused deposition modeling process. Fused deposition modeling is a rapid prototyping technique that builds up three-dimensional objects in layers by extruding molten modeling material in a predetermined pattern according to computer file data representing the mold tool. The computer file data is derived from information available on the desired prototype molded part. For example, typically, the part is designed using a computer-aided design (CAD) system, and corresponding information relating to the outline of the part is derivable from a CAD file defining the desired part. A computer program designs the mold portions in accordance with the outline of the desired part, as the inverse of the desired part shape. A software program available

from Moldflow Corporation will design the mold portions in this manner. A further software program "slices" the computer representation of the mold portions into horizontal layers. The modeling machine extrudes the roads of modeling material layer-by-layer, with each extruded road having a thickness equal to the height of a slice. The extruded material fuses to previously deposited material and solidifies upon a drop in temperature to form the mold portions. The mold portions may be built simultaneously in the modeling machine, or one at a time. In a preferred embodiment, the mold portions 12 and 16 are built from a polyphenylsulfone resin on a Stratasys® Titan™ FDM® fused deposition modeling machine.

The sprue channels 22, the vent channels 24, the alignment holes 26, and any cooling lines are preferably formed into the mold portions 12 and 16 as they are built. This can be done by including such features in the computer file data representing the mold tool 10. Alternatively, a sprue channel, vent channel, cooling lines and/or alignment holes may be machined into the mold portions 12 and 16 after they are built. The channels 22 and 24 and the alignment holes 26 shown in the exemplary mold tool 10 are merely one example of the placement and design of such features. Alternative designs include vertical orientation of the channels 22 and 24, and forming a single sprue channel or vent channel within one or the other of mold portions 12 and 16.

The need for a vent channel in the mold tool 10 may be avoided by controlling the extrusion pattern of the roads so that the mold tool 10 has an inherent porosity providing an open-cell matrix sufficient to vent gas from the mold cavity 19. Controlled porosity fused deposition modeling is taught in U.S. Patent No. 5,653,925.

The mold tool 10 is formed from a thermoplastic resin that is compatible with the fused deposition modeling process and that will sustain the temperature and pressure of the injection molding process, so as to produce at least one prototype plastic injection molded part. An exemplary thermoplastic resin

comprises at least 50 weight percent of a thermoplastic selected from the group consisting of polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamides, polycarbonate, polyaryletherketone, acrylics (e.g., methyl methacrylate), nylon, poly(2-ethyl-2-oxazoline), and blends thereof. The thermoplastic resin may contain various fillers, additives and the like, as will be understood by those skilled in the art. A particularly preferred thermoplastic for use in creating a mold tool in accordance with the present invention is a polyphenylsulfone-based resin.

FIG. 3 shows a flow diagram which summarizes the method of producing a prototype injection molded part in accordance with the present invention. A CAD tool is used to generate computer file data representing a mold tool, in step 40. The data is provided to a fused deposition modeling machine, in step 42. The mold tool is built in the fused deposition modeling machine, in layers defined by the computer file data, in step 44. In an optional step 46, the mold surfaces and/or mating surfaces of the mold tool are smoothed to remove ridges unintentionally created in the formation of the mold tool. In a preferred embodiment, the smoothing is done by a vapor smoothing process, such as is disclosed in a co-pending provisional patent application entitled "Smoothing Method For Layered Deposition Modeling", filed on even date herewith and incorporated by reference as if set forth fully herein (copy attached hereto as Appendix A). As is taught in said co-pending application, certain mold features may be identified for solvent masking or for pre-distortion prior to the vapor smoothing step, and the computer file data representing the mold tool may include data identifying said features. Alternative smoothing techniques include sanding, grinding, and thermal ironing.

The mold surfaces of the mold tool are then coated with a release agent, in a step 48. Suitable release agents include dry film lubricants, and others that will be recognized by those skilled in the art. If needed, sprue and vent channels and alignment holes are machined into the mold tool prior to step 48. A final step 50

is to perform injection molding using the mold tool. The mold tool is assembled in an injection molding machine, without the addition of any reinforcement fill material or layers.

Using the method of the present invention, a prototype plastic injection molded part can be produced within a 24-hour time period.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

CLAIMS:

1. A method for making a prototype plastic injection molded part, comprising the steps of:

providing computer file data representing a mold tool;

building the mold tool by depositing roads of a molten thermoplastic resin in layers in a predetermined pattern defined by the computer file data, the mold tool having two or more mating mold portions, each mold portion having a mold surface, a mating surface, and a base which supports the mold and mating surfaces, the mold surfaces together defining a mold cavity; and

using the mold tool in an injection molding machine, without the additional of any reinforcement fill material or layers, to create the prototype part by injection molding of plastic.

2. The method of claim 1, wherein the thermoplastic resin is a polyphenylsulfone-based resin.

3. The method of claim 1, and further comprising the step of:

vapor smoothing the mold surfaces prior to the step of using the mold tool in an injection molding machine.

4. The method of claim 1, wherein the thermoplastic resin comprises at least about 50 weight percent of a thermoplastic selected from the group consisting of polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamides, polycarbonate, acrylics, nylon, poly(2-ethyl-2-oxazoline), and blends thereof.

5. The method of claim 1, wherein a sprue channel and alignment holes are formed into the mold tool as it is built.

6. The method of claim 1, and further comprising the step of:
machining a sprue channel into the mold tool, prior to the step of using the mold tool in an injection molding machine.

7. The method of claim 1, and further comprising the step of:
machining a plurality of alignment holes into the mold tool, prior to the step of using the mold tool in an injection molding machine.

8. The method of claim 1, wherein the predetermined pattern results in the mold tool having a porosity sufficient to vent gas in the mold cavity generated by injection of the plastic.

9. The method of claim 1, wherein a vent channel is formed into the mold tool as it is built.

10. The method of claim 1, and further comprising the step of:
machining a vent channel into the mold tool, prior to the step of using the mold tool in an injection molding machine.

11. The method of claim 1, and further comprising the step of:
coating the mold surfaces with a release agent prior to the step of using the mold tool in an injection molding machine.

12. The method of claim 1, and further comprising the steps of:

building a mold core by depositing roads of a molten thermoplastic resin in layers in a predetermined pattern defined by the computer file data; and

assembling the mold core in the mating portions of the mold tool prior to the step of using the mold tool in an injection molding machine.

13. The method of claim 12, wherein the thermoplastic resin forming the mold core is an alkali-soluble thermoplastic, comprising a base polymer containing between about 15 weight percent and 60 weight percent of a carboxylic acid, and a plasticizer, and further comprising the step of:

dissolving the mold core from the prototype part.

14. A method for making a prototype plastic injection molded part, comprising the steps of:

providing computer file data representing a mold tool;

building the mold tool by depositing roads of a molten soluble thermoplastic resin in layers in a predetermined pattern defined by the computer file data;

using the mold tool in an injection molding machine, without the additional of any reinforcement fill material or layers, to create the prototype part by injection molding of plastic; and

dissolving the mold tool to release the prototype part.

15. The method of claim 14, wherein the soluble thermoplastic resin is an alkali-soluble thermoplastic comprising:

a base polymer containing between about 15 weight percent and 60 weight percent of a carboxylic acid, and a plasticizer.

16. The method of claim 15, wherein the carboxylic acid is methacrylic acid and .wherein the base polymer further contains an alkyl methacrylate.

17. The method of claim 16, wherein the alkyl methacrylate is methyl methacrylate and wherein the base polymer contains between about a 1:1 to a 1:2 weight percent ratio of methacrylic acid to methyl methacrylate.

18. A method for making a prototype plastic injection molded part, comprising the steps of:

providing computer file data representing a mold tool;

building the mold tool by depositing roads of a molten thermoplastic resin in layers in a predetermined pattern defined by the computer file data, the mold tool defining a mold cavity; and

using the mold tool in an injection molding machine, without the additional of any reinforcement fill material or layers, to create the prototype part by injection molding of plastic.

19. The method of claim 18, wherein the thermoplastic resin comprises at least about 50 weight percent of a thermoplastic selected from the group consisting of polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamides, polycarbonate, acrylics, nylon, poly(2-ethyl-2-oxazoline), and blends thereof.

20. The method of claim 18, wherein the thermoplastic resin is a polyphenylsulfone-based resin.

21. The method of claim 18, wherein a sprue channel and alignment holes are formed into the mold tool as it is built.

22. The method of claim 18, and further comprising the step of:
machining a sprue channel into the mold tool, prior to the step of using the mold tool in an injection molding machine.

23. The method of claim 18, and further comprising the step of:
machining a plurality of alignment holes into the mold tool, prior to the step of using the mold tool in an injection molding machine.

24. The method of claim 18, wherein the predetermined pattern results in the mold tool having a porosity sufficient to vent gas in the mold cavity generated by injection of the plastic.

25. The method of claim 18, wherein a vent channel is formed into the mold tool as it is built.

26. The method of claim 18, and further comprising the step of:
machining a vent channel into the mold tool, prior to the step of using the mold tool in an injection molding machine.

27. The method of claim 18, and further comprising the step of:
coating surfaces of the mold cavity with a release agent prior to the step of using the mold tool in an injection molding machine.

28. The method of claim 18, wherein building the mold tool comprises building two or more mating mold portions and a mold core.

29. The method of claim 18, and further comprising the step of:
vapor smoothing surfaces of the mold tool prior to the step of using the mold tool in an injection molding machine.

30. The method of claim 29, and further comprising the step of:
masking selected portions of the mold tool surfaces with a substance that will inhibit smoothing of the selected portions, prior to the vapor smoothing step.

31. The method of claim 30, wherein the masking substance is applied using an automatic process.

32. The method of claim 31, wherein the automatic process is a jetting process.

33. The method of claim 31, wherein the automatic process is a fused deposition modeling process.

34. The method of claim 31, and further comprising the step of:
identifying the selected portions of the mold tool surfaces for masking accordingly to their geometry.

35. The method of claim 34, and further comprising the step of:
identifying the selected portions of the mold tool surfaces for masking accordingly to their radii of curvature.

36. The method of claim 31, and further comprising the step of:
identifying the selected portions of the mold tool surfaces using a software algorithm that creates a digital representation of the surface area to be protected.

37. The method of claim 36, wherein digital data identifying the surface area to be protected is stored in an .stl file.

38. The method of claim 29, and further comprising the step of:
creating a digital mask of selected portions of the mold tool surfaces for which smoothing is not desired, using a haptic input interface.

39. The method of claim 29, wherein the computer file data represents a version of the mold tool wherein certain features of the mold tool surfaces have been pre-distorted so as to obtain a desired final geometry following the smoothing step.

40. The method of claim 31, wherein the computer file data includes an identification of the selected portions of the mold tool surfaces.

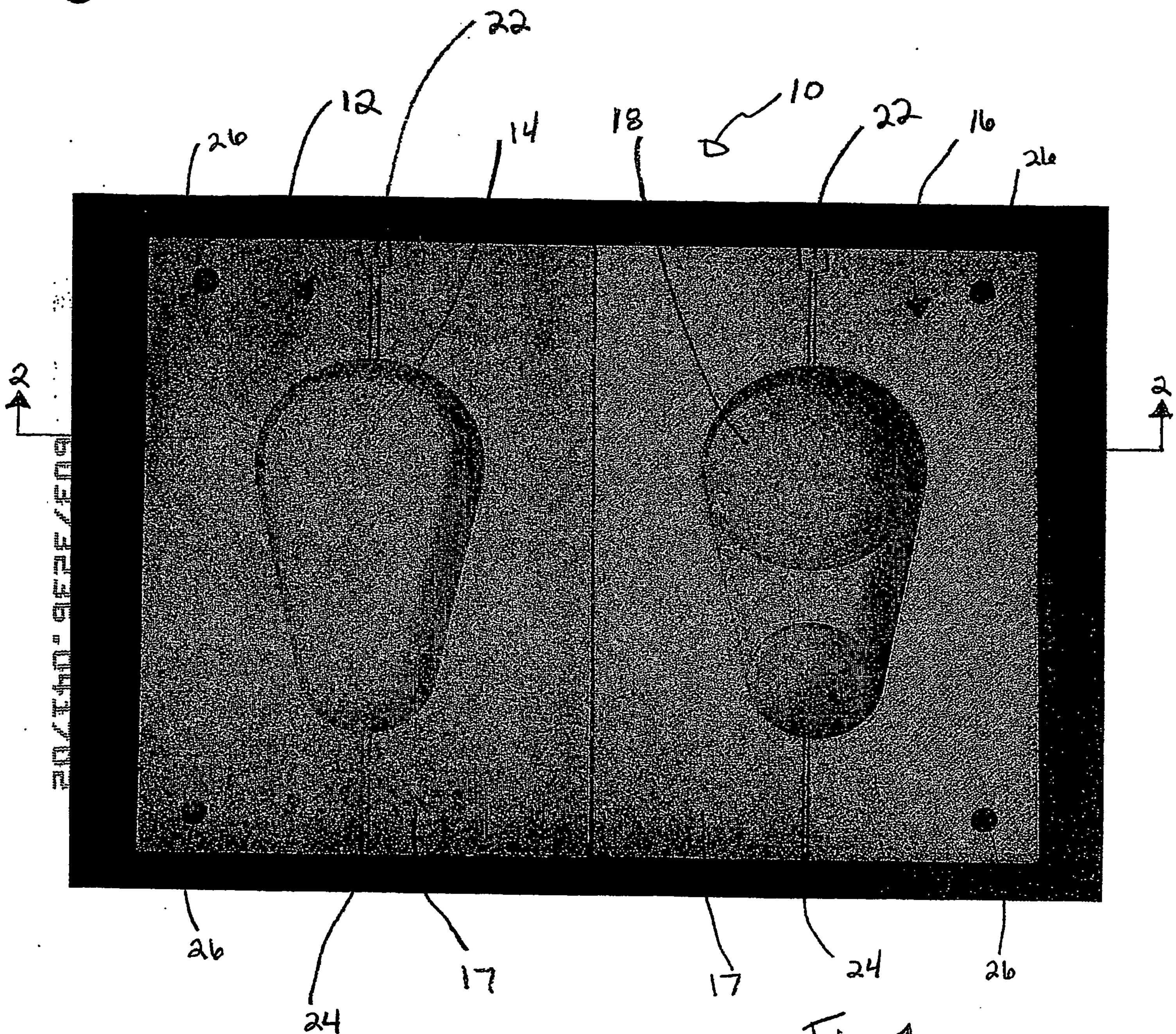


Fig. 1

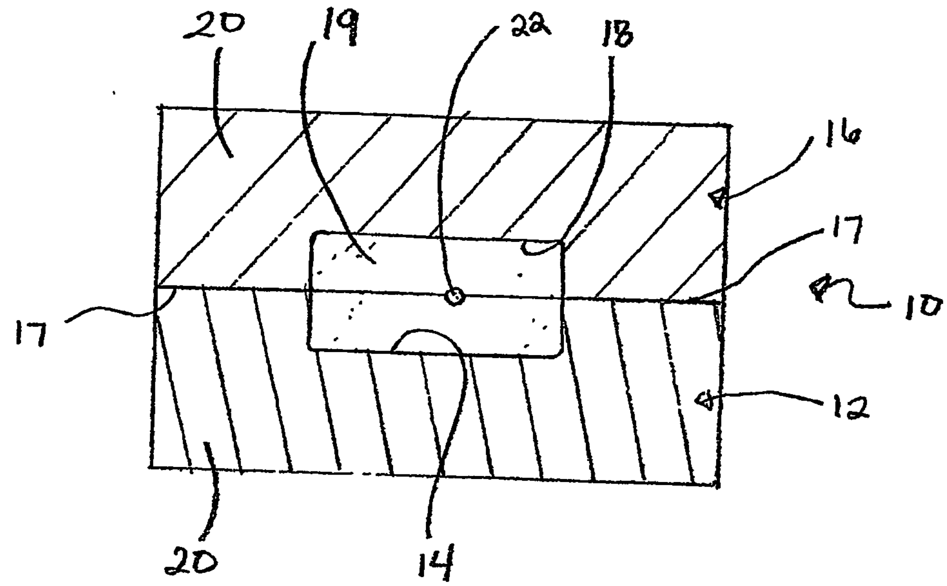


Fig. 2

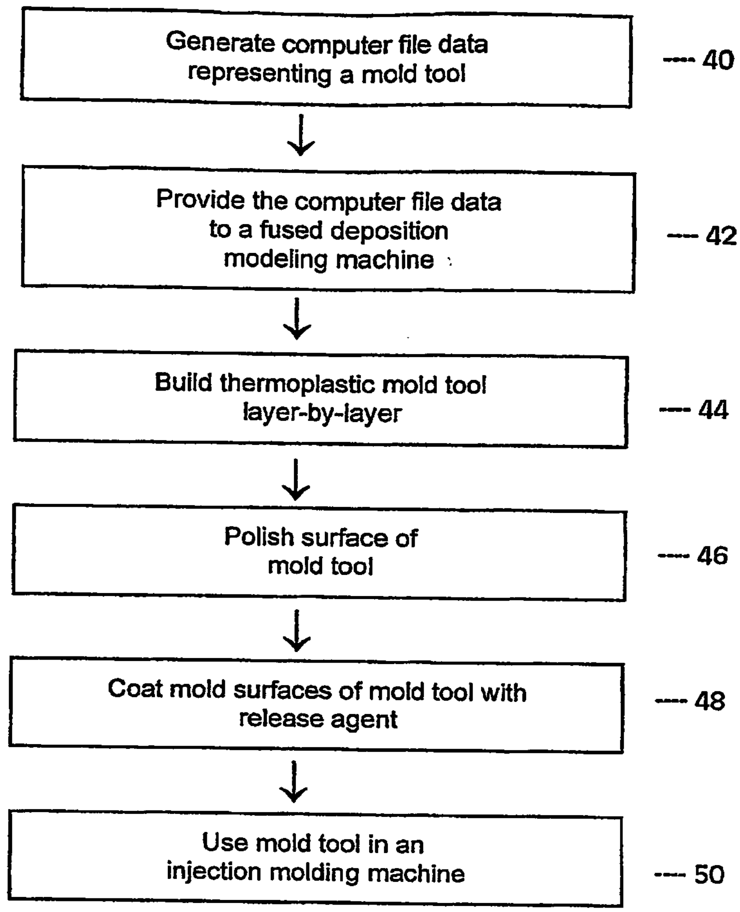

Generate computer file data representing a mold tool
40
Provide the computer file data to a fused deposition modeling machine
42
Build thermoplastic mold tool layer-by-layer
44
Polish surface of mold tool
46
Coat mold surfaces of mold tool with release agent
48
Use mold tool in an injection molding machine
50

Fig. 3

SMOOTHING METHOD FOR LAYERED DEPOSITION MODELING

CROSS-REFERENCE TO RELATED APPLICATION(S)

None.

BACKGROUND OF THE INVENTION

The present invention relates to the field of rapid prototyping, and particularly to methods of achieving surface smoothness in prototype objects made by layered manufacturing.

Production and testing of prototype objects is a commonly used step in developing new products, machines and processes in a wide range of industries. A variety of layered manufacturing methods for forming three-dimensional prototypes are known, which develop prototype objects cheaply and quickly from a geometric computer model under computer control. These rapid prototyping methods generally slice or divide a digital representation of a desired object (computer aided design (CAD)) into horizontal layers, then build the object layer-by-layer by repetitive application of materials. Exemplary rapid prototyping techniques include layered deposition modeling, selective laser sintering and stereolithographic processes.

One example of layered deposition modeling is a fused deposition modeling technique performed by Stratasys® FDM® modeling machines. Fused deposition modeling builds up three-dimensional objects by extruding solidifiable modeling material from an extrusion head in a predetermined pattern, layer-by-layer, based upon design data corresponding to the particular shape of each object layer. Examples of extrusion-based apparatus and methods for making three-dimensional objects are described in Crump U.S. Patent No. 5,121,329, Crump U.S. Patent No. 5,340,433, Danforth et al. U.S. Patent No. 5,738,817, Batchelder et al. U.S. Patent No. 5,764,521 and Dahlin et al. U.S. Patent No. 6,022,207, all of which are assigned to Stratasys, Inc., the assignee of the present invention.

In the Stratasys® FDM® modeling machines of the current art, modeling material is typically loaded into the machine as a flexible filament wound

on a supply reel, such as disclosed in U.S. Patent No. 5,121,329. A solidifiable material which adheres to the previous layer with an adequate bond upon solidification and which can be supplied as a flexible filament is used as the modeling material. Motor-driven feed rollers advance the strand of filament into a liquifier carried by an extrusion head. Inside the liquifier, the filament is heated to a flowable temperature. Flowable modeling material is forced out of a nozzle on the far end of the liquifier, and deposited from the liquifier onto a base. The flow rate of the material extruded from the nozzle is a function of the rate at which the filament is advanced to the extrusion head. A controller controls movement of the extrusion head in a horizontal x, y plane, controls movement of the base in a vertical z-direction, and controls the rate at which the feed rollers advance filament. By controlling these processing variables in synchrony, the modeling material is deposited in "beads" layer-by-layer along tool paths defined from the CAD model. The material being extruded fuses to previously deposited material and solidifies to form a three-dimensional object resembling the CAD model.

The surfaces of objects developed from layered manufacturing techniques of the current art are textured or striated due to their layered formation. Curved and angled surfaces generally have a "stair step" appearance, caused by layering of cross-sectional shapes which have square edge profiles. The stair-stepping effect is more pronounced as layer thickness increases. Although the stair-stepping does not effect the strength of the object, it does detract aesthetically.

Surface roughness of objects created by layered manufacturing techniques also arises from errors in the build process. For example, in the fused deposition modeling systems of the current art, errors can arise due in part to inconsistent extrusion flow rates. Errors particularly occur at start points and end points of the tool path, for instance, at the location of a "seam" (i.e., the start and end point of a closed-loop tool path). These errors can cause undesired inconsistencies in the shape of the resulting model.

Rapid prototyping of three-dimensional objects includes not only the production of prototype parts, but also may include the production of molds. Exemplary uses of molds created with rapid prototyping include forming molds used to create injection molding tool inserts such as described in U.S. Patent No. 5,189,781, and forming fugitive molds for green ceramic pieces prior to sintering such as described in U.S. Patent 5,824,250 and U.S. Patent 5,976,457.

The current art teaches manually trimming, machining or grinding objects formed by layered manufacturing to remove excess material. Buffing with cloths, sand paper or solution-born abrasives are current methods of smoothing or polishing the objects. For example, Hull et al. U.S. Patent 5,059,359, Methods and Apparatus for Producing Three-dimensional Objects by Stereolithography, describes their prototypes as "perfect for smoothing by sanding to yield the right-sized part". The need for hand-finishing of models made from additive process techniques is also recognized in U.S. Patent No. 6,021,358, which utilizes subtractive modeling techniques to attain smooth models. There is a need in rapid prototyping systems of an expedient and relatively inexpensive method of post-processing layered manufacturing prototype objects.

A previously developed technique used in manufacturing of plastics involves the use of chemical vapors or liquids to smooth by reflowing the surface of the plastic, termed solvent polishing. Solvent polishing was developed in the plastics industry over twenty years ago for the purpose of developing a smooth level and/or high gloss coating or surface without needing to exercise extreme care in the application or manufacturing of the items. For example, U.S. Patent No. 3,437,727 discloses a method using chemical vapors for refinishing telephones that were returned to the telephone company as a method of recycling them.

There are two standard methods for solvent polishing articles. The first is to immerse the entire plastic article in a bath of liquid plastic solvent for a period of time based on the solvent and type of plastic involved. This allows the

solvent to penetrate the outer layer of the plastic, thereby causing it to reflow. Reflowing causes the outer surfaces of the plastic article to become smooth and/or shiny.

The second method of solvent polishing is the exposure of the plastic article to vaporized solvent. A handheld vaporizer as shown in U.S. Patent No. 4,260,873 may be used to expose the plastic object. Alternatively, the object can be placed into a chamber filled with a vaporized solvent, generated from a heated bath below, as in U.S. Patent No. 3,737,499. An advantage of the vaporizing chamber is that the solvent is contained and can be recycled, thereby minimizing potential environmental pollution.

The use of hot solvent vapors to melt or plasticize the surface of the substrate has been used in the circuit board manufacturing area to facilitate the transfer of printed circuits, as disclosed, for example, in U.S. Patent No. 4,976,813. Another example is disclosed in U.S. Patent No. 4,594,311, where solvent vapor is used to treat the non-imaged areas of the plastic base material which holds a printed circuit board in order to further enhance the printed pattern and secure it more strongly to the surface. In U.S. Patent No. 5,045,141, a substrate, typically a circuit board, may be treated to facilitate transfer of the printed circuit to it.

Solvent polishing using liquid or vapors is also commonly used as a degreasing or cleaning step in manufacturing processes, especially prior to painting.

Despite the need in rapid prototyping for an expedient and inexpensive surface finishing technique, Applicant is unaware of any teaching or suggestion in the prior art to use a vapor polishing technique for the smoothing of objects formed by layered manufacturing rapid prototyping techniques.

BRIEF SUMMARY OF THE INVENTION

The present invention is a method for smoothing the surface of an object built from a polymeric or wax material using a layered manufacturing rapid prototyping technique. After the object is built, it is exposed to a vaporized solvent for an exposure time sufficient to reflow the object surface. A solvent is chosen based on its ability to transiently soften the material which forms the object, and thereafter evaporate off the object. The object is removed from the solvent and allowed to dry, producing a smooth finished part. Optionally, portions of the object surface may be masked prior to exposing the object to solvent, so as to preserve fine details of the object. Alternatively, portions of the object surface may be pre-distorted prior to exposing the object to solvent, so that said surface portions will attain a desired geometry following vapor smoothing.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective, magnified view illustrating a raw object formed by a layered manufacturing rapid prototyping technique.

Figure 2 is a perspective, magnified view of the object shown in FIG. 1, after undergoing vapor smoothing.

Figure 3 is a diagrammatic view illustrating the process of vapor smoothing an object in accordance with the present invention.

Figure 4a is a cross-sectional detailed view of a portion of a raw object formed by fused deposition modeling.

Figure 4b shows the object cross-section of FIG. 4a after vapor smoothing.

Figure 5a is a cross-sectional detailed view of the object portion shown in FIG. 4a, wherein the object geometry has been pre-distorted in anticipation of vapor smoothing.

Figure 5b shows the object cross-section of FIG. 5a after vapor smoothing.

DETAILED DESCRIPTION

The method of the present invention may be employed with respect to objects formed from a polymeric or wax material using layered manufacturing rapid prototyping techniques. An exemplary layered manufacturing technique is the type disclosed in U.S. Patent No. 5,121,329, wherein an extrusion head deposits "roads" of molten material in layers of predetermined shape, and which material solidifies upon a drop in temperature to form a solid model.

Figure 1 shows an exemplary object 10, formed by a layered manufacturing rapid prototyping technique. The object 10 has an angled surface 12, a curved surface 14, two horizontal surfaces 16, and three vertical surfaces 18. In another embodiment, the object may be a mold tool for use in making prototype plastic injection molded parts, such as is disclosed in a co-pending provisional application entitled "Layered Deposition Bridge Tooling", filed on even date herewith (copy attached hereto as Appendix A). The object 10 is made of a polymeric or wax modeling material, which may also include fillers and other additives as well as dispersed particulate materials. Amorphous thermoplastics are particularly suited for use in the present invention, for instance, ABS, polycarbonate, polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamides, acrylics, poly(2-ethyl-2-oxazoline), and blends thereof. The present invention may also be used to advantage with other polymeric and wax materials, including glass-filled nylon, jetting wax, sintered thermal plastic powders, and green metals or green ceramics dispersed in a polymeric binder.

As shown in FIG. 1, the object 10 is "raw", that is, it has not undergone post-process smoothing. Prior to vapor smoothing in accordance with the present invention, surfaces 12 and 14 exhibit a stair-stepping effect. Surfaces 16 and 18 exhibit striation and roughness.

To smooth the surfaces of object 10, the object 10 is placed in a vaporizer 30, where it is exposed to vapors of a solvent 34. This is illustrated in

FIG. 3. A suitable vaporizer is of the type available from Detrex Corp. of Southfield, Michigan, model VS-2000, although those skilled in the art will recognize that many alternative vaporizers can be used in practicing the present invention.

The solvent 34 is selected to be compatible with the modeling material which forms the object 10. Suitable solvents will react with the modeling material so as to soften and flow the material at the object surfaces. The solvent should also be able to vaporize off the surface of the object, leaving the object intact and unscathed. A preferred solvent for use with a wide range of amorphous thermoplastics is methylene chloride. Other suitable solvents will be recognized by those skilled in the art, for instance, an n-Propyl bromide solution (e.g., Abzol®), perchloroethylene, trichloroethylene, and a hydrofluorocarbon fluid sold under the name Vertrel®.

The vaporizer 30 boils the solvent 34 into a vapor zone 36, which is maintained at or above the boiling point of the solvent. The object 10 is suspended in the vapor zone 36, held by a wire skewer 32, which is bent to fit around the object. Alternative holding means may also be used, such as a basket, a net or a mesh platform. The object 10 is exposed to the vaporized solvent 34, allowing vapors of the solvent 34 to penetrate the surfaces 12, 14, 16 and 18 of object 10. Penetration of the solvent 34 softens the modeling material at the object surfaces, so that the surface material may reflow. Reflowing of the material smooths the object surfaces.

The object 10 remains exposed to the vapors of solvent 34 until a desired surface finish is obtained. An exposure time is selected based on the type of solvent and modeling material, the fineness of the object features, and the concentration of the solvent vapors. The exposure time can be gauged by observing condensation of solvent vapors on the object, or can be pre-selected according to a formula. Condensation will stop when the temperature of the object surface

reaches the temperature of the boiling solvent. This is an indication that solvent penetration has occurred. Using methylene chloride as the solvent 34, an amorphous thermoplastic modeling material will soften and reflow in a short time, typically between about 0.1 seconds to 5 minutes exposure time. If smoothing of an object is expected to occur in a short exposure time, it may be desirable to reduce the concentration of solvent vapors so that the exposure time can be increased. A longer exposure time allows an operator more time to observe the smoothing process and more room for error in removing the object from the solvent vapors.

When the exposure time elapses, the object 10 is removed from the vapor zone 36 and allowed to dry. In a preferred embodiment, the object 10 dries within seconds to minutes after its removal from the vapor zone 36, as the solvent 34 evaporates off of the object 10. The object 10 may then be handled, as it is not sticky, soft or wet. In some cases, such as where solvent exposure time is great or the solvent is highly concentrated, it may be desirable to dry the object 10 in an oven to remove any residual solvent. Oven drying should be done at a temperature greater than the boiling point of the solvent.

Following the vapor smoothing process, the stair steps in surfaces 12, 14, 16 and 18 of object 10 are either significantly reduced or eliminated. The extent of the smoothing achieved for a given object using the method of the present invention will depending upon the exposure time, the solvent, the modeling material, and the initial surface condition of the object. FIG. 2 illustrates a significant reduction in the stair steps and roughness of the object 10, achieved by vapor smoothing.

Optionally, selected features of an object (e.g., features smaller than 0.25 inches, thin walls, corners, convex edges and concave edges) can be masked with a substance that will inhibit smoothing of said selected portions, or, exposure of said selected features to the solvent vapors can be otherwise avoided. For

example, it may be desirable to mask the corners of object 10, to prevent the corners from rounding. Similarly, concave surfaces of an object can be masked to prevent in-flow of surrounding material. Suitable solvent masking substances include those used in printed circuit board manufacturing, such as gums, waxes, pastes, adhesives or masking tape, which may be applied either manually or automatically. Masking may also be accomplished by surrounding a feature with a gas.

Automatic application of a masking substrate may be done, for example, by jetting a masking material onto the surface of selected object features, in a layered deposition process such as is known in the art. A masking substance may also be applied by depositing roads of masking material, using a fused deposition modeling process such as performed by Stratasys® FDM® modeling machines. Those skilled in the art will recognize additional masking techniques know in the art, that may be applied in carrying out the present invention.

When an automatic masking technique is used, the features to be masked may be identified using a software algorithm that creates a digital representation of the surface area to be protected. The protected area may be identified in a digital representation of the object, such as in an .stl file geometry using a CAD system, a Graphic Pixel system or a Voxel system. Alternatively, the surface areas to be masked may be identified by the user via a haptic input interface, such as a FreeForm™ system available from SensAble Technologies, Inc. The haptic input system creates a digital mask of the areas for which smoothing is not desired.

As an alternative to masking techniques, the geometry of an object surface may be pre-distorted in anticipation of the vapor smoothing. The pre-distortion is accomplished by using a software algorithm to modify a digital representation of the object (*e.g.*, a CAD model of the object or a sliced representation of the object as in a .stl file). Using a pre-distortion software

algorithm, feature details are distorted so as to overbuild corners and edges, and underbuild pockets, such that following vapor smoothing such features will attain approximately the desired geometry. More specifically, an exemplary pre-distortion algorithm will: (1) identify geometric features with radii of curvature equal to or smaller than the slice height (*i.e.*, the thickness of a layer); (2) for identified features having a positive radius of curvature (*e.g.*, a corner or edge), the algorithm will build up the initial object representation at such features; and (3) for identified geometric features having a negative radius of curvature (*e.g.*, a pocket or a joint between planes), the algorithm will hollow out the object representation in the vicinity of such features. The pre-distortion software algorithm thus creates a modified object representation, so that the identified geometric features will be distorted by either depositing additional material or depositing less material than is ultimately desired in the final smoothed object. A similar algorithm can be used to identify features for masking.

According to the pre-distortion algorithm, features should be built up by not more than the slice height, for instance, by half of a slice height. The surface roughness of a typical part made by fused deposition modeling is about 0.3 times the slice height. The additional material added in pre-distortion of positive features may be roughly the thickness of this surface roughness, so that when the re-flowed material is pulled away, the solid material left takes on the desired final object geometry. For the negative curvature regions, enough material needs to be removed by the pre-distortion algorithm that the in-flow from the surrounding regions fills in the removed material.

Pre-distortion of object geometry is illustrated in FIGS. 4a and 4b and FIGS. 5a and 5b. FIGS. 4a and 4b show a cross-sectional view of a portion of an object 40 that has not been pre-distorted, superimposed onto an outline 42 illustrating the desired final surface object geometry of object 40 (*i.e.*, the unmodified object representation). As illustrated in FIG. 4b, vapor smoothing

results in rounding of convex corners 44 away from the desired outline 42, and rounding of edges 46 beyond the desired outline 42. FIGS. 5a and 5b illustrate a portion of an object 40' which has the same desired final surface geometry as object 40. Unlike object 40, object 40' has been pre-distorted according to the pre-distortion algorithm of the present invention. As illustrated in FIG. 5a, the pre-distorted surface geometry of object 40 extends beyond the desired outline 42 at corners 44 and concave edges 46. Following vapor smoothing, as illustrated in FIG. 5b, the corners 44 and edges 46 of the pre-distorted object 40 more closely follow the desired outline 42 than do the corners 44 and edges 46 of the object 40.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

CLAIMS:

1. A method for making a three-dimensional object comprising the steps of:

building an object from a polymeric or wax modeling material using a layered manufacturing rapid prototyping technique; and

smoothing an object surface by exposing the object to vapors of a solvent that transiently softens the modeling material.

2. The method of claim 1, wherein the layered manufacturing technique is fused deposition modeling.

3. The method of claim 1, where the modeling material is a thermoplastic resin.

4. The method of claim 3, wherein the thermoplastic resin comprises at least about 50 weight percent of an amorphous thermoplastic selected from the group consisting of ABS, polycarbonate, polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamides, acrylics, poly(2-ethyl-2-oxazoline), and blends thereof.

5. The method of claim 4, wherein the solvent is selected from the group consisting of methylene chloride, an n-Propyl bromide solution, perchloroethylene, trichloroethylene, and a hydrofluorocarbon fluid.

6. The method of claim 1, wherein the modeling material is selected from the group consisting of thermoplastics, green metals dispersed in a polymeric binder, green ceramics dispersed in a polymeric binder, and jetting wax.

7. The method of claim 6, wherein the modeling material is glass-filled nylon.

8. The method of claim 1, and further comprising the step of:
selecting a length of time during which the object is to be exposed to the solvent vapors as a function of concentration of the solvent vapors, prior to the smoothing step.

9. The method of claim 8, and further comprising the step of:
reducing the concentration of solvent vapors so that the selected exposure time will increase.

10. The method of claim 1, and further comprising the step of:
masking selected portions of the object surface with a substance that will inhibit smoothing of the selected portions, prior to the step of smoothing the object surface.

11. The method of claim 10, wherein the masking substance is applied using an automatic process.

12. The method of claim 11, wherein the automatic process is a jetting process.

13. The method of claim 11, wherein the automatic process is a fused deposition modeling process.

14. The method of claim 11, and further comprising the step of: identifying the selected portions of the object surface for masking accordingly to their geometry.

14a. The method of claim 14, and further comprising the step of: identifying the selected portions of the object surface for masking accordingly to their radii of curvature.

15. The method of claim 11, and further comprising the step of: identifying the selected portions of the object surface using a software algorithm that creates a digital representation of the surface area to be protected.

16. The method of claim 15, wherein digital data identifying the surface area to be protected is stored in an .stl file.

17. The method of claim 1, and further comprising the step of: creating a digital mask of selected portions of the object surface for which smoothing is not desired, using a haptic input interface.

18. The method of claim 1, wherein the building step comprises pre-distorting certain object features so that said features will obtain a desired geometry following the smoothing step.

19. A method for eliminating surface roughness of an object built from a modeling material using a layered manufacturing rapid prototyping technique, comprising the step of:

reflowing a surface of the object by exposing the object to vapors of a solvent that transiently softens the modeling material.

20. The method of claim 19, where the modeling material is a thermoplastic resin.

21. The method of claim 20, wherein the thermoplastic resin comprises at least about 50 weight percent of an amorphous thermoplastic selected from the group consisting of ABS, polycarbonate, polyphenylsulfone, polysulfone, polystyrene, polyphenylene ether, amorphous polyamide, methyl methacrylate, poly(2-ethyl-2-oxazoline), and blends thereof.

22. The method of claim 21, wherein the solvent is selected from the group consisting of methylene chloride, an n-Propyl bromide solution, perchloroethylene, trichloroethylene, and a hydrofluorocarbon fluid.

23. The method of claim 19, wherein the modeling material is selected from the group consisting of thermoplastics, green metals dispersed in a polymeric binder, green ceramics dispersed in a polymeric binder, and jetting wax.

24. The method of claim 23, wherein the modeling material is glass-filled nylon.

25. The method of claim 19, and further comprising the step of:
masking selected portions of the object surface with a substance that will inhibit smoothing of the selected portions, prior to the step of reflowing the surface.

26. The method of claim 25, wherein the masking substance is applied using an automatic process.

27. The method of claim 26, wherein the automatic process is a jetting process.

28. The method of claim 26, wherein the automatic process is a fused deposition modeling process.

29. The method of claim 26, and further comprising the step of: identifying the selected portions of the object surface for masking accordingly to their geometry.

30. The method of claim 29, and further comprising the step of: identifying the selected portions of the object surface for masking accordingly to their radii of curvature.

31. The method of claim 26, and further comprising the step of: identifying the selected portions of the object surface using a software algorithm that creates a digital representation of the surface area to be protected.

32. The method of claim 31, wherein digital data identifying the surface area to be protected is stored in an .stl file.

33. The method of claim 26, and further comprising the step of: identifying the selected portions of the object surface for masking using a haptic input interface.

34. A method for making a three-dimensional object comprising the steps of:

providing an initial object representation in a digital format, the initial object representation having a surface geometry;

modifying the initial object representation to pre-distort certain features of the surface geometry, producing a modified object representation;

building an object as defined by the modified object representation, from a modeling material using a layered manufacturing technique; and

vapor smoothing surfaces of the object to produce a finished object, the finished object having a surface geometry that approximately matches that of the initial object representation.

35. The method of claim 34, wherein the layered manufacturing technique is fused deposition modeling.

36. The method of claim 34, wherein the modeling material is a thermoplastic and the vapor smoothing step comprises exposing the object to vapors of a solvent selected from the group consisting of methylene chloride, an n-Propyl bromide solution, perchloroethylene, trichloroethylene, and a hydrofluorocarbon fluid.

37. The method of claim 34, and further comprising the step of:

identifying the selected portions of the object surface for masking accordingly to their geometry.

38. The method of claim 37, and further comprising the step of: identifying features of the surface geometry for pre-distortion according to their radii of curvature.

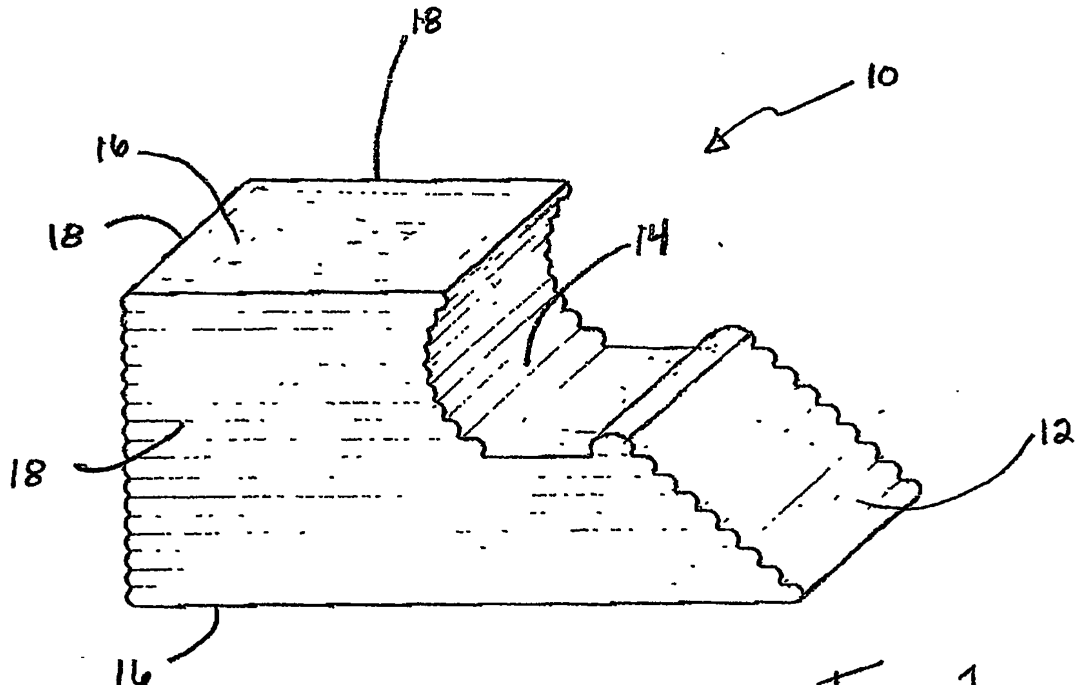


Fig. 1

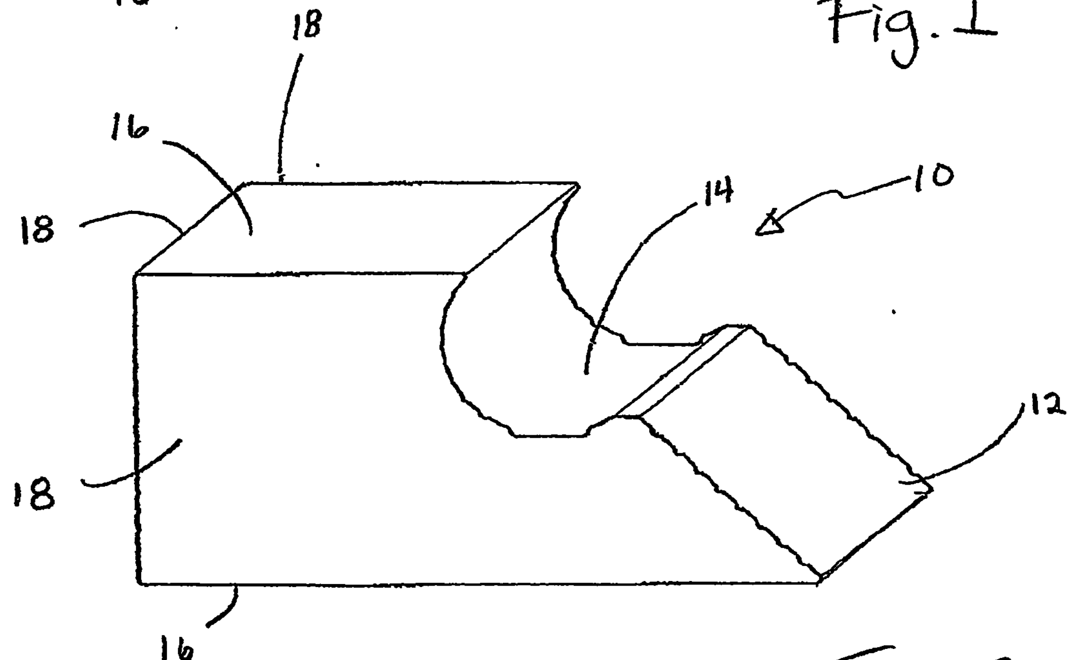


Fig. 2

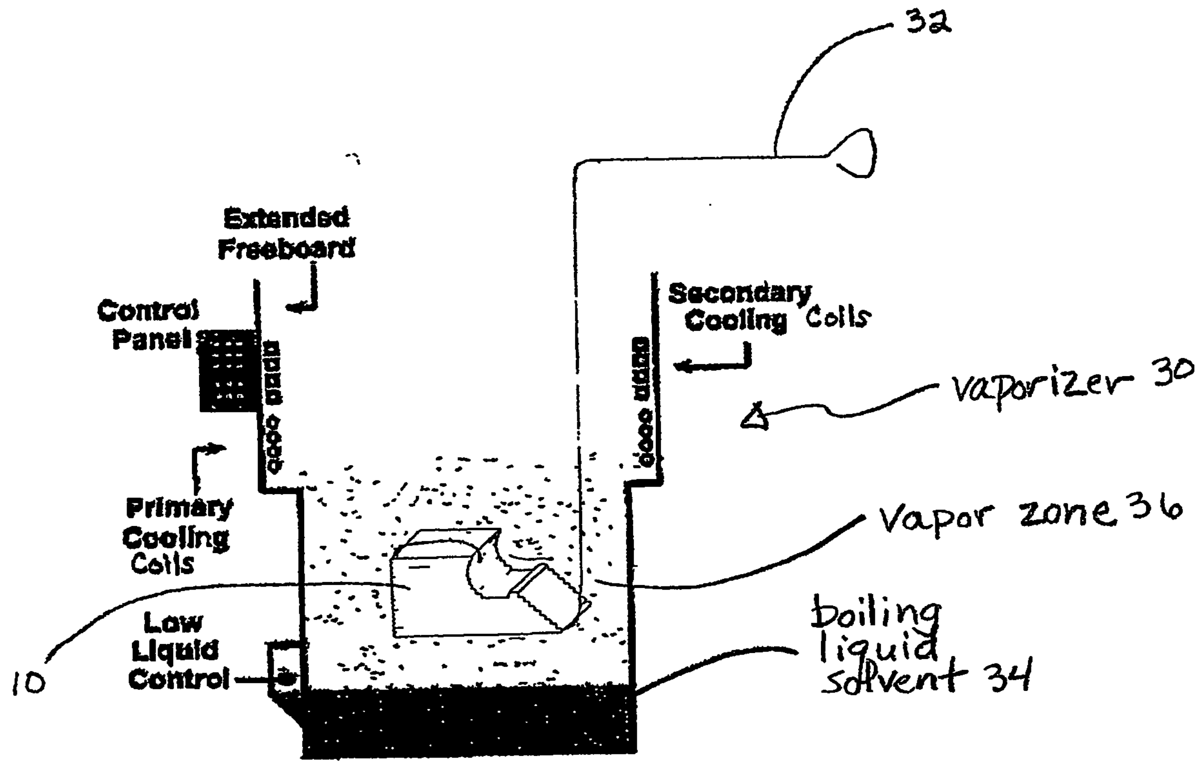

32
Extended Freeboard
Control Panel
Secondary Cooling Coils
vaporizer 30
Primary Cooling Coils
Vapor zone 36
boiling liquid solvent 34
10
Low Liquid Control

Fig. 3

Fig 4A

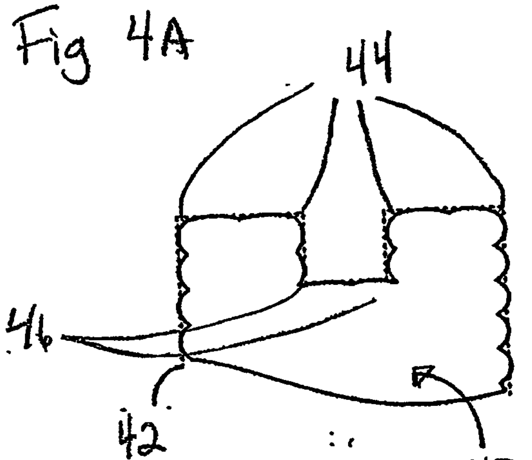
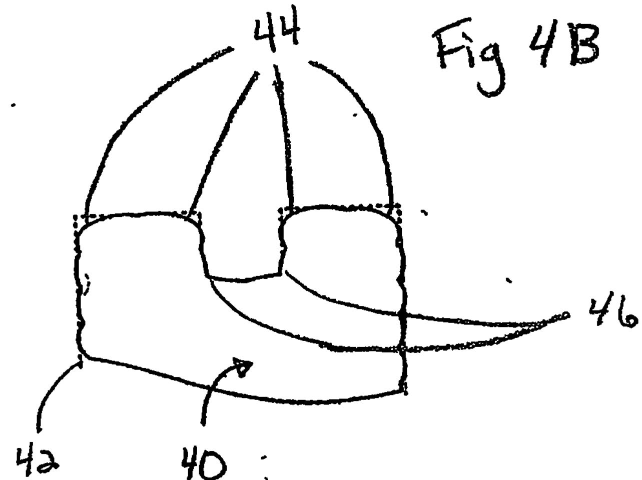


Fig 4B



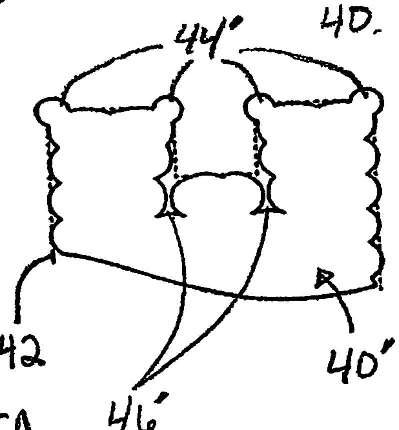


Fig. 5A

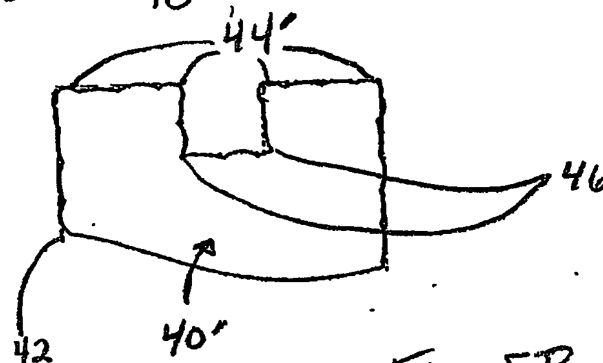


Fig. 5B